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Particle Acceleration in the Heliosphere

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Abstract. The heliosphere is filled with supersonic solar wind that forms shocks wherever it encounters obstacles, be they a high speed Coronal Mass Ejection (CME), or regions where fast-solar wind encounters slower-moving solar wind. Energetic particles (> 10 s of keV/nuc to 10s of MeV/nuc) associated with these shocks form a test bed for understanding particle acceleration since the shock properties can often be measured and energetic particle composition compared to candidate seed populations. Over the past 15-20 years a wide body of evidence has emerged showing that generally the seed population is the suprathermal ion pool at energies above the bulk solar wind. Understanding the interplanetary suprathermal ion population is therefore a critical step in fully understanding the physical mechanisms that accelerate particles in interplanetary space.

Keywords: Particle acceleration: interplanetary space – Interplanetary space: energetic particles, pickup ions, solar wind plasma – Shock waves: interplanetary

PACS: 96.50.Pw, 96.50.Vg, 96.50.Ya, 96.50.Ci, 96.50.Fm

INTRODUCTION

The interplanetary medium at 1 AU is filled with multiple heliospheric particle populations extending in energy from < 1 keV/nuc hundreds of MeV/nuc. Figure 1 shows a multi-year sum from ACE spacecraft instruments extending from the slow- and fast-solar wind peaks around 1 keV/nucleon, through the suprathermal range to energetic particles up to 10s of MeV/nucleon. Above solar wind energies transient enhancements lasting for days to weeks at a time are caused by shock-associated (Gradual) Solar Energetic Particles (SEPs), Corotating Interaction Regions (CIRs), and impulsive SEPs [1-3]. At the highest energies are the comparatively steady Anomalous Cosmic Rays and Galactic Cosmic rays discussed elsewhere in this volume.

Since the solar wind is continuously present in the heliosphere with intensity far exceeding the higher energy populations, it had been considered obvious that when shocks formed in the solar wind at CMEs or CIRs, that the solar wind itself provided the seed population. In the period up to the early 1990s when solar wind composition was only roughly known, the hypothesis that solar wind provided the seed particles did not contradict the available observations. However, with the detailed measurements of solar wind on Ulysses [4] and of energetic particles from ACE, this situation changed.

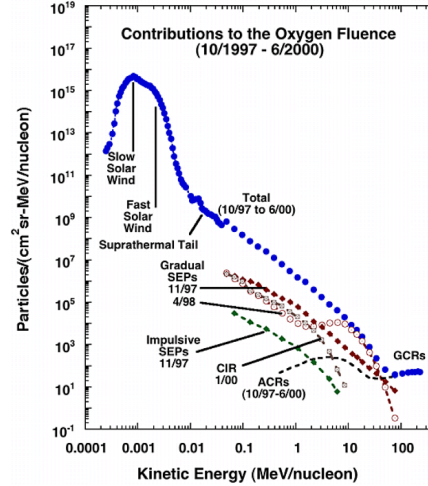


FIGURE 1. Fluence of O ions measured at 1 AU by instruments on the ACE mission over the period Oct. 1997 - June 2000, from Mewaldt et al. [5]

OBSERVATIONS

“Tracer” ions in energetic particle populations have been used to identify sources of the energized particles by detecting abundances of species known to be extremely rare in the solar wind: ^3He (solar wind abundance $\sim 1/2500$ of ^4He [6]), and He^+ (virtually absent in the solar wind which escapes from the million-degree corona).

Figure 2(a) shows examples of energetic ^3He accelerated by a shock on Oct. 12, 2000, where $^3\text{He}/^4\text{He}$ was $\sim 5\%$, a factor of ~ 100 higher than in the solar wind; significant ^3He enhancements were seen in about one-half of the 56 events surveyed [7]. Figure 2(b) shows ^3He in shock-associated SEPs at about $\sim 5\times$ solar wind abundance [8]. About one-half the solar flares surveyed showed such enhancements [8, 9].

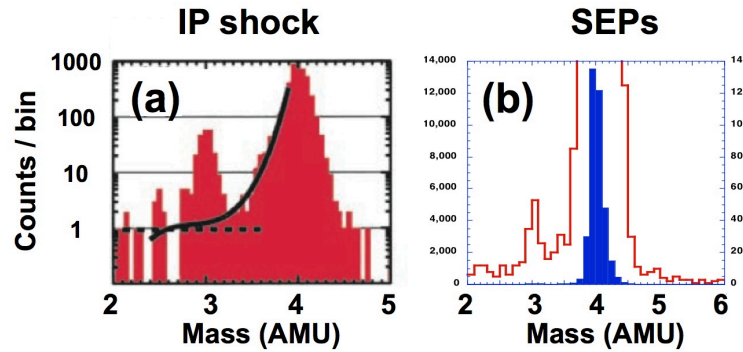


FIGURE 2. (a): He mass histograms showing tracer isotope ^3He accelerated in an interplanetary shock and (b) in shock-associated solar energetic particles (*right*), from Desai et al. [7] and Mason et al. [8]. Outlined trace in (b) is ^3He (right scale), filled peak is ^4He (left scale).

Figure 3(a) shows He^+ in CIRs, which is observed routinely at levels of 25% of He^{++} [10]. In Figure 3(b) the $\text{He}^+/\text{He}^{++}$ ratio is plotted for a 1-year period showing very large enhancements that appear in coincidence with interplanetary shock acceleration events [11].

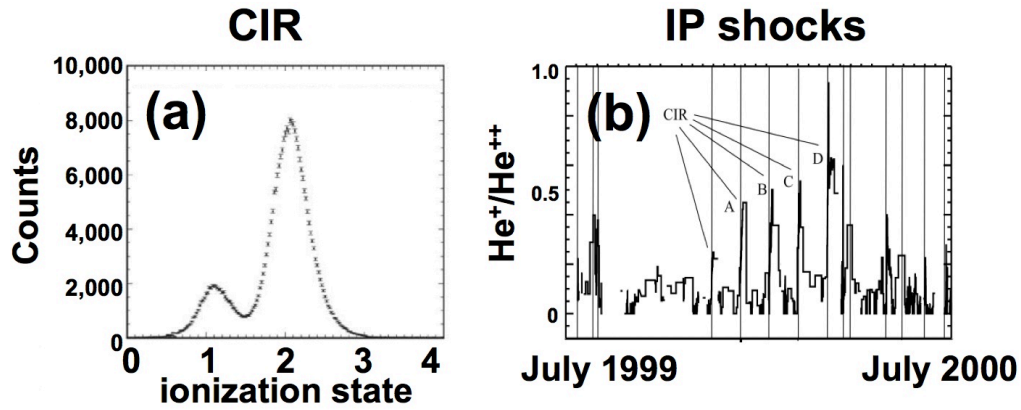


FIGURE 3. (a): Ionization state histograms of tracer ion He^+ accelerated in a Corotating Interaction Region (CIR) and (b) $\text{He}^+/\text{He}^{++}$ ratio in several shock passages showing large abundances of He^+ , which is absent in the solar wind as it leaves the Sun. From Möbius et al. [10] and Kucharek et al. [11]

What are the sources of these tracer ions? For ^3He the source is small solar particle acceleration events that show extreme enhancements where $^3\text{He}/^4\text{He}$ can be >1 [12]. These events are extremely frequent in solar active periods, when ^3He is found to be present in the interplanetary medium at ACE a majority of the time [13]. The He^+ comes from interstellar neutral He which enters the heliosphere and is ionized close to the Sun, and thence becomes a pickup ion in the solar wind [14]. At several AU, where the solar wind abundance decreases by $\sim 1/r^2$ but the pickup ions do not, the $\text{He}^+/\text{He}^{++}$ ratio in CIRs can be >1 [15].

If the tracer ^3He and He^+ comes from the remnant SEP and pick-up ion sources that are in the suprathermal ion population, what about the major ion species?

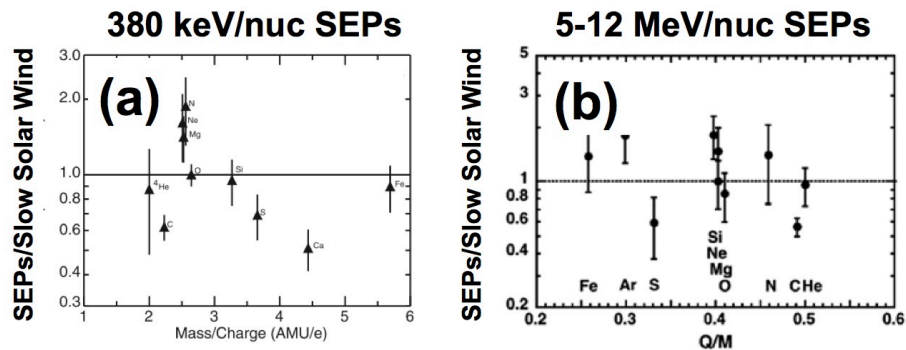


FIGURE 4. Ratios of SEP major ion abundances plotted by M/Q and Q/M ratio to slow solar wind composition, normalized to O, at low energies (a) and higher energies (b). Deviations from a simple relationship are evidence that the differences are not caused by the acceleration mechanisms but are rather due to the energetic particle origin in the suprathermal ion population. From Desai et al. [16] and Mewaldt et al. [17].

Figure 4 shows the ratio between SEP abundances averaged over many events and compared to the slow solar wind at (a) 380 keV/nuc and (b) 5-12 MeV/nuc. The points are ordered by M/Q or Q/M ratio which would be expected to organize the data since it is proportional to gyroradius. The fact that the deviations do not follow any

simple pattern is consistent with the source population coming from a source other than the solar wind [16, 17].

DISCUSSION

The presence of tracer elements with high abundances in heliospheric shock-associated SEPs and CIRs shows that the solar wind is not the primary source for the energetic particle population, since no mechanisms have been identified that could produce the observed composition from fractionation of solar wind. The picture is far from complete, however, since surveys of the heliospheric suprathermal ion pool are in their early stages. It is already known that the pool shows systematic abundance changes that vary with solar cycle where SEP activity enhances the suprathermal Fe abundance during active periods [18], and this appears to be reflected in CIR abundance variations over the solar cycle [19]. These observations establish that the seemingly small advantage suprathermals have over the bulk solar wind give them a decisive preference in particle energization. Characterizing the seed population in the suprathermal ion pool will thus be a critical component for a full understanding of shock acceleration in the heliosphere.

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